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Recommended boundary for controlled groundwater area in Montana near Yellowstone National Park

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UNABRIDGED

RECOMMENDED BOUNDARY

for

CONTROLLED GROUNDWATER AREA IN MONTANA

NEAR YELLOWSTONE PARK

Prepared for

Water Resources Division

NATIONAL PARK SYSTEM
U.S. DEPARTMENT OF INTERIOR

for presentation to:

MONTANA
RESERVED WATER RIGHTS COMPACT COMMISSION

by

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I. INTRODUCTION

The geothermal resources of Yellowstone National Park are an important national treasure which should be protected. Such protection was one of the reasons for establishment of the Park and this commitment continues today (U.S. Congress, 1992). Development of geothermal resources similar to those found in the Park have impacted surface hydrothermal features and geothermal systems in other regions of the world (eg: Allis and Lumb, 1992; Bradford, 1992; Cody and Lumb, 1992; Bjornsson and Steingrimsson, 1992; U.S. Congress, 1992; Kerr, 1991; Narasimhan and Goyal, 1984, Allis and Barker, 1982; Allis, 1981; Donaldson, 1979; Hatton, 1970; Boulton, 1970; Studt, 1958). These impacts have occurred in response to development for domestic and hotel use (Allis and Lumb, 1992; Bradford, 1992) as well as at power generation facilities (Narasimhan and Goyal, 1984; Allis and Barker, 1982). Aware of the potential for geothermal development adjacent to the Park, the Montana Reserved Water Right Compact Commission and the Water Resource Division of the National Park System are discussing the implementation of a Controlled Groundwater Area to protect the geothermal resource from impact by groundwater development outside the Park. The Controlled Groundwater Area would be promulgated under Montana water law, and would apply only to those areas adjacent to Yellowstone National Park in Montana.

A technical working group was organized to assist with definition of the boundaries of a Controlled Groundwater Area. The working group was constrained to literature-based analysis because of the short time-frame (3 months) between task identification and the deadline for recommendations. The short time frame was necessary to provide input to the 1993 Montana Legislature for consideration.

Review of the literature demonstrates that there are little hard physical data with which to describe and quantify the geothermal flow system in the Park. Even in well-known systems the high cost of monitoring wells, which may need to be thousands of feet deep limit hydrogeologic information at the resource-area margins. Data which would be required include water temperature, total head at both shallow and deep levels in both the recharge and discharge areas, measured transmissivity and storativity, as well as geologic data on subsurface stratigraphy, primary hydrogeologic units, structure, fracture location, fracture width, anisotropy and heterogeneity. Although some data exist, much of the critical data do not exist and cannot be reasonably expected in the near future. Similarly, in New Zealand, "...(there is a) large amount of data available for a relatively shallow, horizontal slice of part of the field, but very poor information on the depth dimension of the field. ... This limits the accuracy of even conceptual hydrological models of the field which usually indicate the location of an "up-flow zone" at several kilometers depth, and the location of boiling and dilution processes in "outflow zones" typically within a kilometer of the surface." (Allis and Lumb, 1992, p. 14.) The working group considered the application of numerical models to assess impacts. This approach was rejected for Yellowstone National Park because of data limitations.

A literature review was conducted for developed geothermal fields in the world where **both** an impact **and** a diameter of effect field was reported (Table 1). This data might be used to delineate a Controlled Groundwater Area Boundary. The data were limited to developments in hydrothermal-flow systems similar to that in Yellowstone Park (magmatic heat source in a bimodal caldera complex where the system is dominantly a high-temperature hydrothermal system as opposed, for example, to a vapor-dominated system) (Fournier and others 1976; Fournier and Pitt, 1985). Some problems with exact analogy exist because of the hydrostratigraphic impacts of the cratonic sedimentary package into which the Yellowstone caldera complex has intruded. Impacts from geothermal development, such as land subsidence have been reported over diameters ranging from 1 to 7 miles, pressure drops over distances from 0.5 to 10 miles and changes in heat flow and geyser activity over a distance of about one mile (Table 1).

Four points should be kept in mind when reviewing Table 1. First, subsidence is a good first estimate of impact distance, however, the pressure effects from development likely extend farther from the development center than the measured subsidence distance. Second, to conclude that any development no matter how small would produce effects at the largest distance would be incorrect. The effects reported in Table 1 resulted from high rates of water removal (5000 to more than 70,000 gpm) continuously over several years with little reinjection. Some of the effects might have been smaller if the appropriate modern practice of reinjection had been utilized. None-the-less, data in Table 1 do provide perspective regarding the distance of impact that could occur should large-scale development be contemplated. Third, diameters not radii are reported. Thus the tabulated values are conservative since the diameter of influence is twice the radius of influence. Fourth, the diameter of influence generally includes all wells in the development system. Thus, the distance to the edge of the measured impact may not be very far from the outermost extraction well. One should not conclude from data in Table 1 that a single well is responsible for the measured impact.

The literature review was supplemented by a hydrogeologically based conceptual model which used the geologic framework and hydrologic principles (Toth, 1962) to assess where impacts might be expected. This approach was based on topographic analysis (Toth, 1962). The approach does not account for the effects of changing head on the groundwater divide. Furthermore, the topographic approach has limitations in stratigraphically controlled hydrothermal-flow systems where recharge may be other than at the topographic divides, where thermal buoyancy causes water to rise. However, topographic analysis does provide a first order estimate of recharge, and stratigraphic effects can be accounted for at least conceptually.

Table 1. Maximum reported diameter of impact from developed geothermal areas described in the literature.

Impact	Distance	Location	Source
Subsidence	1.2mi	Wairakei NZ	Hatton, 1970
Subsidence	2 mi	Wairakei NZ	Hatton, 1970
Subsidence	4 mi	Wairakei NZ	Allis and Barker, 1982
Subsidence horizontal component	4.7 mi	Broadlands NZ	Narasimhan and Goyal, 1984
Pressure drop	10 mi	Tauhara NZ	Allis, 1982
Pressure drop	1.7 mi	Wairakei NZ	Allis and Barker, 1982
Pressure drop	0.5 mi	Wairakei NZ	Studt, 1958
Subsidence horizontal component	2 mi	Wairakei NZ	Narasimhan and Goyal, 1984
Subsidence	1.4 mi	Wairakei NZ	Narasimhan and Goyal, 1984
Heatflow change	1 mi	Wairakei NZ	Allis, 1979
Subsidence	7 mi	Iceland	Bjornsson and Steingrimsson, 1992
Subsidence	3.8 mi	Broadlands NZ	Narasimhan and Goyal, 1984
Subsidence/uplift	22 mi	Cerro Prieto	Narasimhan and Goyal, 1984;

Note: Cerro Prieto data may be influenced by tectonics.

The definition of a geothermal resource is of interest since this resource is to be protected. A variety of perspectives was examined ranging from the heat resource, developable heat resource, hot groundwater, the surface expression of hot groundwater (eg: hydrothermal alteration, hot ground, hot pools, hot springs, mud pots, geysers), and the tourist resource which is attracted by the surface expression of the geothermal resource. The consensus reached was that the hydrothermal-flow systems in Yellowstone National Park, parts of which extend outside the Park, constitute the geothermal resource. This approach was adopted because these flow systems form the underpinnings of all hydrothermal features and processes both surface and subsurface. Geothermal-resource protection requires that all parts of the flow system (recharge, transmission, and discharge) be carefully monitored, evaluated, and regulated if the resource inside the Park is to be protected.

Control means that groundwater withdrawal or injection be regulated where such groundwater use effects a hydrothermal system in the Park. Control does not mean that all activity would be eliminated since prohibition of all withdrawal irrespective of whether it effects the Park would be an anti-development mode. Rather, control means that inventory, monitoring and regulation would be used to assure that no impact to the Park results from use of wells in the Controlled Groundwater Area. This control (inventory, monitoring and regulation) must be exercised such that human activities outside the Park do not demonstrably impact the hydrothermal-flow systems in the Park.

The working group was encouraged by the Reserved Water Rights Compact Commission staff and Water Rights Staff of the National Park System to encompass within the Controlled Groundwater Area all regions that might reasonably be expected to influence the Yellowstone National Park hydrothermal systems so that those with groundwater activities in this region could be notified monitoring, evaluation, and the possibility of regulation. Those outside the area could expect not to be brought under control, and could expect no increased regulation under Montana law. "If there is the least doubt that an area might be part of the hydrothermal-flow system, part of which is in the Park, that area should be placed in the Controlled Groundwater Area. Unless you are absolutely certain there is no effect expected in this area, assume there is an effect" (Owen Williams, National Park Service).

<u>The objective is to delineate a Montana Controlled Groundwater Area for the long-term protection of the hydrothermal systems in Yellowstone National Park.</u>

II. RATIONALE USED FOR ESTABLISHING BOUNDARIES OF A CONTROL ZONE

A. System Concept

The Working Group recognizes that surface hydrothermal features of Yellowstone Park are merely the uppermost portions of several thermo-hydraulic systems driven by heat sources at depth. The system includes recharge, transmission, heating, and discharge components.

Recharge to the system begins with water which enters the shallow system either through the alluvium, through direct shallow entry into transmissive formations or through the very-near surface parts of fracture systems. Because of the large area in which recharge can occur, impact to this system is very difficult unless withdrawals are large, focused on fractures, or cumulative effects impact recharge over large areas. Not all shallow surface recharge is connected to the deep system. A small part is transmitted at depth in fractures and transmissive formations. These may be sealed from the surface at depth. Impacts to recharge may occur in these deeper transmission areas if withdrawal quantities are very large or focused on an important transmission zone connected directly to the main hydrothermal system. If data come to show that cold-water recharge is not important to recharge of the hydrothermal-flow system, then restraints on well usage should be relaxed.

When recharge water encounters the heat source, the water is heated, becomes less dense, and starts to rise. This density contrast contributes to the driving force which is responsible for near-vertical-upward flow associated with the central portion of the hydrothermal-flow system. As the hot water rises toward the surface, it commonly interacts with near-surface cold water. Surface features may develop with highly variable and changing expression of the dynamic interaction between cold and hot flow systems. Manifestations include fumaroles, hot or boiling springs, geysers, hot pools, and mud pots. The feature formed depends on heads, temperatures, self-sealing, rock water interactions, and other dynamic factors. These features typically overlie the core of the hydrothermal system. On the margins of the core, the hot water floats over more dense cold-water and overlies the cold-water recharge portion of the flow system. Warm springs are commonly found in such areas.

The shallow, cold water surroundings which receive some thermal waters are not normally connected directly to the hydrothermal system except in the zone of mixing. Discharges from springs and shallow wells, which carry a thermal signature (possibly chemical) should be regarded as a mixture of shallow, cold groundwater and hot water from a deeper thermal system, until contrary evidence is developed. Protection of the Park hydrothermal system requires that withdrawals from the flow systems outside of the Park produce no impact inside the Park. This requires that recharge to the hydrothermal system not be substantially reduced or disrupted, and that development in areas of thermal discharge from the Park not reduce heads in

the hydrothermal-flow system within the Park. In principle, out-of-Park use of warm water discharged naturally from the Park could be allowed so long as the manner of capture is not projected or observed to impact the hydrothermal system in the Park.

B. BASE MAPS USED TO DRAW THE BOUNDARY

1. Topographic Base. The working group used 1:250,000 AMS topographic maps as the base. The topography (200 foot elevation contour interval) was used to estimate recharge and discharge elevations (see below).

2. Surface Hydrothermal Features. A map of the surface hydrothermal features was transferred by enlargement from White and others (1988). A map of thermal features was also produced from an Arc/Info computer file by Yellowstone National Park Geographic Information staff with the caveat that the data were incomplete in the northern part of the Park. Our research to date suggests that no single complete compilation of all surface geothermal features exists for Yellowstone Park at this time. The compilation from White and others (1988) and data from a map of hydrothermal springs in Wyoming (including Yellowstone National Park) were also used (Heasler and others, 1983) and constitute the best published data.

The thermal features are widely known to change naturally (eg: Bargar, 1978). Thus the position and even the behavior of a single feature cannot be considered constant even under natural conditions. Changes may be induced by processes such as chemical precipitation, changes in precipitation regime, changes in the rock due to earthquakes and rock fracture. Furthermore, the surface expression of the hydrothermal system at Yellowstone National Park simply represents the fringes of the rising hydrothermal-flow system. Although the surface expression of the system's edge is often what comes to mind when one thinks of the issue of protection of the geothermal resource arises as an issue, to successfully protect this resource, the total flow system rather than the surface feature should be the focus of the control activities. For this reason, the map of surface hydrothermal features and thermal springs was used primarily to estimate elevations and was used to help guide the working group with regard to reasonable recharge elevations.

3. Hydrothermal Recharge-Discharge Areas. Recharge areas for thermal water in Yellowstone Park are important to the flow system as are the discharge areas for such a system. Accurate determination of the location of such areas is extremely difficult without an inventory of hydraulic-head data, groundwater temperature data and heat-source data. In the absence of such data, a watershed analysis was utilized. The recharge elevations are probably not higher than the discharge elevations because the potential energy of the hydrothermal-flow system is dictated in part by the elevation of the recharge area. (The potential energy is dictated by the elevation of the recharge area and drives the local and regional

groundwater flow systems. Energy loss due to friction during transmission is unknown and unaccounted for, but may be balanced in part by another unknown, energy addition from buoyant forces due to heating.) A watershed map was constructed which shows the surface-water drainage divides and their relationship to the Park Boundary. Areas where surface water flows into the Park were assumed to be areas of groundwater recharge. Areas where surface water flows out of the Park were assumed to be areas of groundwater discharge. The Park Boundary is the divide between surface-water flow systems at several locations. In these areas a groundwater no-flow boundary (neither into nor out of the Park) was indicated.

There is some evidence that this approach is reasonable. Discharging thermal water in alluvial systems is known in the Yellowstone Valley and in the Madison Valley near West Yellowstone and Hebgen lake (Sonderegger and Bergantino, 1981). Thermal water is also thought to exit the Park in these areas based on geochemical arguments (Fournier and others, 1976; Friedman and Norton, 1990; Sorey, 1991). Recharge to the hydrothermal-flow system from an area to the north outside Yellowstone National Park is suggested by hydrogen isotope data (Rye and Truesdell, 1992). The current data suggests that sources capable of delivering water with this signature must occur at high elevations north of the Park.

There are at least two areas where recharge-discharge relationships based on the above criteria are highly uncertain. One is along the northern Park Boundary near where Bear Creek enters the Yellowstone River. Technically, Bear Creek forms a confluence with the Yellowstone River outside the Park. Just down stream, however, the Yellowstone River flows back into the Park and Eagle Creek also flows into the Park to join the Yellowstone. The Yellowstone again leaves the Park near Phelps Creek. The drainage divide separating inflow (recharge) and outflow (discharge) was taken to be at the Eagle Creek divide in this area. Recharge is indicated east of this divide and discharge to the west. A second uncertain area is on the west margin of the Park near where Grayling Creek leaves the Park. Here Tepee Creek enters the Park and immediately leaves the Park as part of Grayling Creek. Again, recharge was assumed until no drainages flow into the Park with the Tepee Creek drainage divide forming the recharge area boundary.

4. Madison Group Outcrop. Recharge to the hydrothermal system is probably not constrained to surface-water divides in all areas. In particular, the Mammoth Hot Spring flow system is thought to be related to flow in the Madison Aquifer (Struhsacker, 1976; Bargar, 1978; Sorey, 1991). The Madison Aquifer may also contribute water to other hot springs with travertine such as Terrace Springs near Madison Junction. Given the fact that the Madison Group is known to be important regionally and contains both dolomite and solution porosity and permeability in the area (for example, see Clarke, 1991 for a summary) the working group assumed that outcrops of the Madison Group, particularly above 6200 feet above sea level, should be considered candidates for recharge to the hydrothermal-flow system in Yellowstone

National Park. As a result, an overlay of surface outcrops of Madison Aquifer rocks was compiled from a variety of sources.

The primary sources for Madison Group outcrop data include an unpublished preliminary geologic map compilation for the Bozeman 1 x 2 degree AMS sheet. This preliminary compilation was prepared by Dr. Donald Smith at a scale of 1:125,000 in the early 1980's at the Department of Earth Sciences at Montana State University in Bozeman, MT. No such coverage is known to exist for the Ashton, Billings or Cody AMS sheets. Madison Group outcrop areas in Montana covered by sheets other than the Bozeman sheet were compiled from Lovering (1929), Ross and others (1955), Egbert (1960); Witkind (1969, 1972a, b; 1975, 1976); U.S. Geological Survey (1972 b); Prostka and others (1975); Fraser and others (1969), and Pierce (1987). Many of the primary maps provide little information on the attitude (dip and strike) of the Madison Aquifer. At a few locations, dip and strike were plotted near the outcrops on the map to provide a sense of the structural geology for the units. One must recognize that much of the geologic mapping in this region has been at the reconnaissance level, and that numerous contradictions exist in the literature regarding the precise location of the Madison Aquifer. Such problems could not be resolved in the time frame required for this project. Although positions of the Madison Aquifer are in some cases uncertain, the general position of the outcrops as depicted on the Madison Aquifer Outcrop overlay are approximately correct.

5. Alluvium. In addition, discharge occurs through alluvium. Sources for general information about alluvium include Ross and others (1955); U.S. Geological Survey (1972a); Pierce (1973); Fournier and others (1976); Friedman and Norton (1990), and Clarke, (1991); Sorey (1991). No overlay of alluvium was made, but interpretations depended on the sources listed.

6. Faults. Another significant geologic avenue for recharge and discharge is along faults. A geologic overlay of faults was created. The position of the faults is known with varying degrees of certainty, but did help guide the working group regarding the role of faults in the region. The sources are the same as those indicated above. In addition, new work and syntheses by Personius (1982), Schmidt and Garahan (1983), and Sorey (1991) were incorporated on the overlay.

III. CONTROLLED GROUNDWATER AREA BOUNDARY DESCRIPTION

A. SCALE

The scale at which the Controlled Groundwater Area Boundary is drawn is important both for practical and philosophical reasons. Common map scales exist which might serve as a base map (eg: 1:1,000,000; 1:500,000; 1:250,000; 1:100,000; 1:125,000; 1:62,500; and 1:24,000). The scale chosen depends in part upon

availability. Additionally, scale influences the manageability of the boundary at meetings and for presentations. More importantly, scale impacts the map-readers' perception of boundary precision. Finally, and most importantly, scale influences how the human mind perceives the system. The working group selected a scale of 1:250,000 (1 X 2 degree U.S. Army Map Service Topographic Sheets (AMS Sheets). This scale is available as a topographic map with 200 foot contours. The scale allows presentation of Yellowstone National Park and the areas adjacent to the Park in Montana in a form that can nominally be handled as a wall or table map. This scale also represents, qualitatively, a degree of uncertainty regarding the precision of the boundary line which will be discussed subsequently.

Several other scales were rejected. The 1:24,000 scale topographic maps are not available throughout the area of interest. The 1:62,500 scale maps are currently out of print, but a few exist. This scale was explored. The assembled maps were judged too large for presentation and imply too high a degree of precision. While data from these maps were used for elevation control, this scale was rejected. 1:100,000 topographic sheets were considered. Topographic maps at this scale exist for all of Wyoming, but this scale was rejected because critical sheets in Montana along the northern Park Boundary are not yet complete. The scale 1:125,000 was considered because of the availability of topographic maps of the Park, but again, no topographic maps at this scale exist outside of the Park. A base map at a scale of 1:500,000 was considered because the state geologic map is at this scale, but no topographic map is available at this scale, and the working group felt that the precision implied by this scale might be too generalized. For this reason, smaller scale maps were rejected. The 1:250,000 scale topographic map base was selected because of its availability, the precision the scale implies, and the manageability of the map for presentation at meetings and in regulation.

B. BOUNDARY TYPES

Several boundaries are shown on the Controlled Groundwater Area Map. The outer-most boundary is the line which separates those areas within the recommended Controlled Groundwater Area and those outside the Controlled Groundwater Area. The rest of the boundaries are nested within the Controlled Groundwater Area and separate different parts of the hydrothermal-flow system (recharge area (R-1 and R-2); discharge area (D-1 and D-2)) and different control objectives. This section describes the location of the areas and the basis upon which the boundaries were drawn.

1. Controlled Groundwater Area Boundary. The Controlled Groundwater Area Boundary for the hydrothermal-flow systems was drawn in working-group sessions with input from other professionals who were able to attend the session and from external technical reviewers who were available to read the document on short notice and wished to comment (see acknowledgements). The outermost boundary was delineated based on the distribution of the topographic divides, Madison Group

outcrop and potential subcrop, possible fracture systems, and their implications for recharge, transmission, and discharge in the hydrothermal-flow system. The entire Controlled Groundwater Area Boundary can be broken into four major component areas in Montana. The factors that controlled the boundary position are summarized moving clockwise along the Park Boundary from the southwest to northeast.

a. **Area One.** The first area extends from the Montana-Idaho border to the Hebgen Fault on the northern margin of Hebgen Lake. The outermost boundary for this area was drawn from the northwestern end of the Bald Peak Syncline where the Madison Group outcrops along the Montana border, along the Paleozoic/Precambrian Contact, across the Precambrian rocks to the edge of the alluvial fill material of the obsidian sand plain (Pierce, 1979) thought to contain discharging thermal water, and then north to the Hebgen Fault (see Controlled Groundwater Area Map).

This area is thought to encompass the hydrothermal-flow system for several reasons:

1. There is some warm-water discharge at the surface in the Hebgen Lake area (1:250,000 Ashton Quadrangle). Although these springs stopped flowing after the Hebgen Lake Earthquake, thermal discharge from the Park is possible in this area.

2. There is weak evidence of elevated temperature in a well at Bakers hole (16 degrees Celcius (C)) as well as in a flowing artesian well at the Povak Ranch (John Sonderegger and Wayne Hamilton, 1992, personal communication).

3. Hydrothermal outflow is also indicated by the chloride flux leaving this part of the Park (Fournier and others, 1976; Friedman and Norton, 1990).

4. The area contains the Bald Peak syncline which involves Madison-Group rocks, plunges toward the Park, and may recharge thermal systems in the Park (Witkind, 1972a). Hot springs to the south east on the Park Boundary occur on trend with the axis of the syncline and may be connected.

5. The area is in a region of tectonic extension (Sbar and others, 1972; Witkind, 1972a; Bailey, 1977; Qamar and Stickney, 1983).

6. The area is close to the caldera rim (Smith and Christiansen, 1980; Christiansen and Hutchinson, 1987; Taylor and others, 1989).

7. The area is active seismically (U.S. Geological Survey and others, 1964; Qamar and Stickney, 1983)

b. Area Two. The second area extends from the Hebgen Fault along the north edge of Hebgen Lake (see Controlled Groundwater Area Map). The boundary turns north roughly following the western edge of the Madison Group rocks in the Madison Range. This margin is the west limb of a south-east plunging synclinorium (Ross and others, 1955). Mississippian rocks are part of the structure and may potentially recharge the system. Some deep recharge in fractures may also occur in this area. Based on what appears to be a fault cutoff near Cameron, Montana (Tysdal and others, 1986) the boundary was carried across the synclinorium north of the Madison Group outcrops to the Gallatin River and down the Gallatin River to the point where the River crosses the Madison Group. This crossing point is a good boundary location since the Gallatin River would probably constitute a constant-head boundary if the River recharges the limestone in this area. The boundary then extends to the Gallatin River-Yellowstone River divide on an azimuth that connects this part of the boundary to the known southwestern extent of the Paradise Valley-Deep Creek fault system (Personius, 1982).

This second area is thought to encompass the hydrothermal-flow system for several reasons:

1. The area encompasses surface-water flow (recharge) to the Park based on topographic evidence and watershed analysis along the western boundary of the Park to the north of the Hebgen Fault.

2. The boundary encompasses potential recharge from Madison Aquifer down the plunge of a synclinorium. (The plunge of the synclinorium is uncertain, but is potentially toward the Park (Ross and others, 1955).)

3. Comparison of Madison Group outcrops with elevation data on the base map show Madison Group elevations of more than 10,000 feet. These elevations are consistent with heads at mapped thermal springs in the Park.

4. There are travertine-bearing thermal springs in the northwest part of the Park along the caldera rim (Terrace Springs) which conceivably could be related to Madison-Group recharge outside the Park.

5. The deuterium data suggest high-altitude recharge is possible from this region (Rye and Truesdell, 1992).

c. Area Three. A third area extends from the known end of the Deep Creek extensional-fault system to connect with the northern part of the Eagle Creek Watershed Divide (see Controlled Groundwater Area Map).

This third area is thought to encompass the hydrothermal-flow system for several reasons:

1. There is geochemical (chloride) and isotopic (helium) evidence that the geothermal system MAY be connected along fault systems extending out of the Park called by some the Reese Creek-Gardiner fault system at LaDuke Hotspring (Sorey, 1991).

2. The structures are connected to hydrothermal outflow in this area (Struhsacker, 1976; Sorey, 1991)

3. The deuterium data suggest recharge from this area is possible (Rye and Truesdell, 1992).

4. Sulfur isotope data suggest anhydrite sources likely associated with Madison Group (Sorey, 1991).

5. There is some magnetotelluric evidence of a heat source near Bunsen Peak (Sorey, 1991).

6. The area is near visible extensional-fault scarps on the eastern margin of the Paradise Valley extensional fault system (Qamar and Stickney, 1983; Personius, 1982).

b. Area Four. The boundary for the fourth area extends from the western Eagle Creek Drainage Divide along the drainage divide that sheds surface water into the Park. This divide extends to the Wyoming border and is the Park Boundary, where the Park Boundary is the divide near Cooke City, Montana ((see Controlled Groundwater Area Map).

This area is thought to encompass the hydrothermal-flow system because:

1. The isotopic evidence suggests recharge is possible here (Rye and Truesdell, 1992).

2. Watershed analysis of surface-water flow suggests groundwater recharge.

3. The area encompasses the Madison Group near Cooke City, Montana and rocks in the area are likely fractured (Pierce and others, 1973; Pierce, 1987).

2. Subareas within the Boundary. Inside the Controlled Groundwater Area Boundary are four subareas (two recharge and two discharge). There is a region of potential recharge to the hydrothermal system that is outside the topographic divides which control surface-water flow into the Park. These areas are recharged through the Madison Aquifer or deep fractures (R-1) and flow toward the heat source and then to the hydrothermal-discharge areas. There is a second area of recharge within the topographic drainage divides which shed shallow groundwater through alluvial

all into the Park (R-2). No interaction is now known between the shallow alluvial (R-2) recharge and the hydrothermal-flow system, but deuterium data permit the possibility of high-elevation recharge to the hydrothermal system.

In general, all regions of probable hydrothermal discharge are collected together (D-1). Additional monitoring and control are desirable for discharging hydrothermal water directly adjacent to the Park (D-2) because of possible interactions between head decline outside the Park and heads in the hydrothermal system in the Park. The distance is difficult to establish without site-specific data. However, even low level use of hydrothermal water at Rotorua in New Zealand by domestic and hotel users was sufficient to impact thermal features nearby. The New Zealand government eventually cemented shut hydrothermal- production wells within 1 mile of Pohutu Geyser. Within months, the pressure levels recovered and the Pohutu geyser returned to normal behavior (Allis and Lumb, 1992). Although there are no geysers directly adjacent to Yellowstone National Park, this distance multiplied by a safety factor of two seems prudent for increased vigilance. While one might justify distances of up to 8 miles for a buffer strip based on impacts in other regions, such impact distances have historically been associated with large-scale withdrawals for power generation and can be addressed under D-1 controls. In some cases deep recharge occurs via the Madison Group or fractures which may exist below the shallow recharge areas or thermal discharge areas. In such areas two letter designations appear with the first the dominant and the second the secondary concern (eg. R-1 + D-1).

3. Boundary-Line Precision. Review of the criteria used to locate the Controlled Groundwater Area Boundary reveals that the precision of the line is low. While one might be tempted to draw a razor sharp line around the area (and indeed one could), the actual line should be viewed as a broad line best drawn with a wide pen. On the other hand, although the line is generalized, the position of the line was drawn to encompass certain hydrologic and geologic features and so should be viewed as carefully located given the data available.

IV. Baseline Data Collection and Monitoring

There are three tasks related to assessment of impact on the hydrothermal system in Yellowstone National Park. The first task is characterization of baseline conditions. The second task is establishment of long-term trends in water levels and chemistry outside of developed areas at selected sites, so that impacts from development can be placed in a regionally unimpacted framework. The third task is monitoring of specific groundwater development activities where such monitoring is warranted.

The groundwater characterization of groundwater from wells and springs has been broken into four categories, based upon the heat content of the water. The

temperatures selected are based on White and Williams (1975). Normal temperatures are less than 59 degrees Fahrenheit (F; 15 degrees Celsius, C); thermally anomalous waters range from 59 to 90 degrees F (15 to 32 degrees C); warm waters range from 90 degrees F up to but not including boiling (the temperature of boiling will vary as a function of altitude, but is approximately 200 degrees F (93 degrees C) within the Park; and hot if the temperature exceeds 200 degrees F. Thermometry is discussed by Rybach and Muffler (1981). The intensity of baseline data collection and analysis should be tied to the temperature category and intensity of use (see tables which follow).

A. Baseline Data

Baseline data collection should consist of:

1. An inventory of springs and thermal features within the Park, within at least two miles of the boundary.

2. An inventory of wells, springs and thermal features outside the Park, but within the Controlled Groundwater Area, is desirable. All wells should be inventoried. As a minimum springs within two miles of the boundary should be inventoried.

3. Geophysical characterization (see implementation).

The importance of solid base-line data through time cannot be over-emphasized. At Rotorua, researchers "....described many changes, not all of which are necessarily or obviously consistent with declining geothermal field. There is a background of both decline and recovery of individual features against which it is difficult to detect a consistent trend, and it is only through a broad-based approach, which looks at the field as a whole, that this has been possible" (Cody and Lumb, 1992, p. 218). Natural changes and variability can easily obscure changes due to human impacts. For example, monitoring-well levels at Rotorua in New Zealand were affected by natural changes, withdrawal changes, barometric changes, rainfall pattern changes, long-term rainfall changes, temperature changes, and boiling changes (Bradford, 1992, p. 234-5) The same can be expected for other parameters. If one is to know of impacts to the system, the natural temporal and spatial variability of the system must be recognized and accounted for in the inventory and baseline-data-collection programs. The National Park Service should increase its mandated inventory and monitoring of thermal features.

Because drilling is not considered a viable option within the Park, all sampling will have to be from natural discharge areas. The inventory of springs and thermal features within the Park should include water temperature, discharge rate, and chemistry.

The inventory of wells, springs and thermal features outside of the Park should include elevation of the well or spring (low-resolution global positioning is urged as a minimum since topographic-map-elevation data are inadequate for analytical purposes), depth to water or shut-in pressure for wells or flowing wells, temperature, specific conductance, discharge for springs and pumping rate for wells, and chloride content.

A representative sampling of existing wells requires both areal distribution and wells completed in different hydrogeologic units. For the purposes of this baseline, the two major units are bedrock and unconsolidated fill materials. In addition to standard requirements for well-drillers reports, permitting for new wells should require the driller or owner to provide well information including location to quarter-quarter-quarter-quarter section, ground elevation at the well, and temperature. Inspection of reports for compliance is recommended. For wells with temperatures greater than 59 degrees F, or discharges greater than two acre feet per year, or areas where cumulative effects are a concern, additional requirements may be imposed, such as measurement of specific conductance (SC), and chloride. Equipment for SC and chloride determination might be maintained for driller/owner use by the National Park Service at Mammoth and West Yellowstone. Measurement and reporting requirements are graduated based on temperature and metered water use. A useful reference on the chemistry of geothermal systems is Ellis and Mahon (1977).

If possible five randomly selected wells or springs in each of the subarea categories (R-1, R-2, D-1, D-2; 20 sites) should be sampled for "complete" chemistry, gas analyses, and isotopic analyses described in the table footnotes. The purpose is to supply background data as a reference against which later measurements from developed areas can be compared, analyzed and interpreted.

Geophysical baseline data should be collected within and along the borders of the Park to provide a reference data set. Within the Park, non-invasive geophysical techniques for gathering baseline data and for monitoring possible impacts are appropriate and potentially very useful. Monitoring of earthquakes within or near the Park provides useful data and should be continued, preferably with an enlarged network. For monitoring purposes, shallow, microearthquake activity should receive increased emphasis.

Another potentially useful data set would be provided by microgravity and precision elevation measurements. For purposes of monitoring any potential effects from development, any effects due to tectonic sources would have to be determined and subtracted (i.e., this is needed baseline data prior to any significant development). Other passive geophysical techniques, such as magnetotellurics and self potential surveys, that could be useful for monitoring the potential effects of geothermal development should be investigated. For any of the non-invasive

geophysical techniques, participation at the federal level will be required because of equipment and cost constraints.

B. Long-Term Reference Data Collection.

A program is needed to collect reference data through time. Some wells and springs inside and outside the Park should be selected after the baseline characterization program is completed. The decision as to which wells and springs and what data is required should be left to the Technical Advisory Board since decisions should be based on the results of the characterization. Quarterly monitoring early in the program could be followed by annual monitoring later under the guidance of the Technical Advisory Board.

C. Monitoring

The following monitoring approach is recommended:

1. All wells must be metered, and provide annual reporting of appropriate items in the following tables:

Table 2. Reporting and monitoring requirements within R-1 R-2 and D-1 Subareas.

Temperature	Q< 2 acre-ft/year[1]	Q> 2 acre-ft/year
<59 degrees F	Q and T	Q, T, and WL[2]
60-89 degrees F	Q, WL, Chloride, SC and T	Q, WL, Chemistry[3], & T, for production well
90-200 degrees F	Q, T, Chemistry[4], 2 monitoring wells[7]	Q, T, Chemistry[6], Geophysical update[5], 4 monitoring wells[7]
>200 degrees F	Q, T, Chemistry[6], Geophysical update, 4 monitoring wells[7]	Additional regs besides those for < 2 acre-ft/year[7]

Table 3. Reporting and monitoring requirements for D2 Subareas.

Temperature	Q< 2 acre-ft/year[1]	Q> 2 acre-ft/year
<59 degrees F	Q, T, WL	Q, T, SC and WL[2]
60-89 degrees F	Q, WL, Chloride, SC and T	Q, WL, Chemistry[3], SC & T, for production and 2 monitoring wells[7]
90-200 degrees F	Q, T, Chemistry[4], Geophysical update[5], 2 monitoring wells[7]	Q, T, Chemistry[6], Geophysical update, 4 monitoring wells[7]
>200 degrees F	Q, T, Chemistry[6], Geophysical update, 4 monitoring wells[7]	Additional regs besides those for < 2 acre-ft/year[7]

[1]This category (use less than 2 acre-ft per year) requires that the well not exceed 6 inches in diameter, that the pump not exceed 2 horsepower, and that the well not exceed 300 feet in depth.

[2]Both static and pumping water levels required.

[3] Complete chemistry including all inorganic major, minor, and trace constituents normally analyzed by EPA certified laboratories. This analysis will help both with system analysis and assessment of potential health concerns associated with use of thermal water as a drinking-water supply. Values for pH, temperature, specific conductance, and alkalinity should be determined in the field.

[4]Chemistry to include additional components (gases or isotopes) at the discretion of the regulatory agency. Careful attention must be paid to correct sampling procedures for the gas analysis. Sampling procedures should be guided by the Technical Advisory Board.

[5]An annual microgravity and precision elevation survey may be required before production begins upon the recommendation of the Technical Advisory Board/Regulatory Agency when deemed appropriate.

[6]Chemistry should include <u>all</u> relevant isotopes and gases in addition to a complete inorganic analysis. Gas chemistry should include, but not be limited to, the following: N_2, NH_3, CO_2, CH_4, H_2, H_2S, and the noble gas series ^3He, ^4He, ^36Ar, and ^40Ar, in order to characterize the water(s) being produced for comparison with Park waters (Sorey, 1991). Sampling procedures should be guided by the Technical Advisory Board.

[7]Data to be reviewed/analyzed by the Technical Advisory Board and/or regulatory agency identified in Section V.

Outside of the Park but within the Controlled Groundwater Area, the Regulatory Agency will periodically analyze hydraulic head data and assess cumulative impacts. In areas of recharge transmission to the hydrothermal system, the depth and geologic location from which a well draws water largely determines its threat to the hydrothermal-flow system in the Park. Deep wells, that are cased to exclude water from alluvium and near-surface bedrock, may draw from rocks or zones that are largely isolated from the extensive shallow recharge system but directly connect recharge to the hydrothermal-flow system. Wells cased to specifically withdraw water from the Madison group rocks or a highly transmissive fracture system requires individualized attention to data obtained by post-drilling tests to insure recharge to the hydrothermal system is protected.

Any wells that produce waters that qualify as warm or hot will need more intensive monitoring and/or analysis to assure that they will not impact the Park's hydrothermal system. Geophysical baseline information would be required when warm or hot waters are encountered within the Controlled Groundwater Area, and large-scale withdrawals are contemplated. Data collection should consist of characterization adequate to indicate the depth and lateral extent of the reservoir zone. Microgravity and precision elevation surveys should be implemented prior to production and be followed by microgravity and precision elevation surveys through time as deemed necessary by the Technical Advisory Board. Additional geophysical information may be required by the Technical Advisory Board.

Thermal water development within this zone will require intensive monitoring of both pressures or water levels and water chemistry (liquid and contained gases). Initial characterization of water levels or pressures and of the thermal-water chemistry at the production site(s) and the monitoring network must be very complete. These data will become the baseline used to indicate whether a change in the water chemistry or hydraulic gradient is occurring. Any significant change such as a 50 percent increase in chloride levels that suggests that thermal water from the Park is becoming a larger component fraction in the production water will be considered grounds for presuming that the Park is at risk. Significant reduction or cessation of water production is required. The regulatory agency with the advice of the Technical Advisory Board is responsible for determination of which alternative is required. Other tests of significant change may be implemented by the Regulatory Agency in consultation with the Technical Advisory Board.

When monitoring wells at a site are required, the monitoring network must consist of two to four wells in addition to the development well. The monitoring wells will normally trend toward the Park, or be keyed toward the source zone as indicated by the geophysical study. These wells must be completed in the production horizon

and be shown to respond to the production-well pumpage or production. When four wells are required, the outer well may not be able to show response to the development production initially, it must be completed so that the water chemistry strongly indicates that these wells are part of the same flow system. When monitoring wells are required, the regulatory agency should review and approve the locations of monitoring wells prior to installation, and should review the adequacy of the performance after installation.

Extreme care should be used in any baseline or monitoring program where wells are used. Proper design of the wells is imperative. Indeed one could argue that installation of even a monitoring well directly adjacent to the Park could constitute a threat to the hydrothermal system since wells can decrepitate or can be designed incorrectly. If pressures are high, leakage or new flow at the surface can have the same effect as development even if development does not occur.

2. Buffer Zone (D-2). The recommendations above would not preclude an appropriator from drilling a well directly adjacent to the Park to extract thermal water. Clearly, a withdrawal at the Park Boundary would very likely (though not certainly) impact the hydrothermal-flow system in the Park. This leaves the question, how far from the Park Boundary should every well which withdraws water warmer than 15 degrees C be scrutinized individually for impact on the Park. This distance is of course difficult to estimate without site-specific data. However, even low level use of hydrothermal water at Rotorua in New Zealand by domestic and hotel users was sufficient to impact thermal features near by. The New Zealand government eventually concreted in wells using thermal water within 1 mile of Pohutu Geyser (Cody and Lumb, 1992). Within months, the pressure levels recovered and the Pohutu geyser returned to normal behavior (Bradford, 1992). Although there are no geysers directly adjacent to the Yellowstone National Park, this distance times a factor of safety of two seems prudent for well-by-well analysis of well effect and cumulative effects regardless of pumping rate. This buffer zone at 2 miles is recommended as a minimum.

V. Implementation

A Technical Advisory Board, with members familiar with Montana's geothermal resources and/or geothermal exploitation, should be instituted to meet as needed to assist the Department of Natural Resources and Conservation in administering this Controlled Groundwater Area. One function of the Board should be technical assistance in the updating or modification of the criteria and/or boundary of the Controlled Groundwater Area. A second function of the Board would be to provide technical assistance on the assessment of cumulative effects of development within the Controlled Groundwater Area. A third function is to periodically review hydrologic data relevant to protection of the Park to determine whether the system may be impacted. A fourth function is recommendations regarding a long-term

reference data collection. A fifth function is review of monitoring plans where required.

The use of a Technical Advisory Board follows the model established for the Long Valley, California, KGRA, (Farrar and Lyster, 1990; Lyster, 1991) and should utilize representatives from the geothermal industry, state agencies (DNRC, RWRCC, DHES, EQC, MBMG), federal agencies (USGS, NPS, USFS, SCS, EPA), the consulting profession, and possibly the university community. The key is to have representatives that understand geothermal systems and the application of geophysical and geochemical data in understanding flow systems. In order to safely permit development of thermal waters while still protecting the Park, an understanding of the controls on the system being developed is mandatory. The function of this committee should be solely technical. Technical review would occur annually, or when the DNRC Water Rights Bureau was concerned about a particular well or application and determined that more detailed review appropriate. Political review of projects and impacts would fall to a political group (RWRCC or the like).

Water-related data collection, storage, and dissemination be assigned with funding to the Groundwater Information Center in the Montana Bureau of Mines and Geology.

If no funds are allocated for characterization, baseline, or long-term reference data collection, one would have to question the commitment to protect the hydrothermal system in the Park.

VI. Additional comprehensive data collection needs.

Several additional data collection efforts are strongly recommended to assist with interpretation of inventory, baseline and monitoring data.

1. Complete a map of surface geothermal features in Yellowstone National Park.

2. Review of the geologic mapping adjacent to the Park indicates that significant work remains to be done to understand the structural and stratigraphic architecture of the system. As a minimum, well constrained compilations of geology on the Bozeman, Billings, Cody, and Ashton 1 x 2 degree AMS quadrangles is needed. In addition, much field work on the geology remains to be done both on the surface and in the subsurface (geophysically) below the Gallatin Volcanic Field. Once compilation is complete, detailed mapping in problem areas at 1:100,000 or even 1:24,000 may be necessary in some areas.

3. Experiences elsewhere suggest that changes due to development can be detected, but only if data before development are known. In the case of subsidence, a very sound network of precision elevation data is needed. Such a network might be

established in conjunction with a well-head elevation measurement program for efficiency, but reoccupation of older topographic survey points should not be ignored. Analysis must recognize the potential for a tectonic component in the elevation-change data as well as the possibility of human-induced components. Monitoring of microearthquakes should also be encouraged. Exploration of thermal infrared, microgravity, magnetotelluric surveys is recommended. None of these data should be considered a substitute for a sound long-term reference data collection.

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